



Full Length Article

Prediction of unburned carbon and NO formation from low-rank coal during pulverized coal combustion: Experiments and numerical simulation



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HIGHLIGHTS

- The DTF experiment was successfully modeled one-dimensionally.
- The reaction kinetics of coal char heterogeneous combustion was obtained by TGA.
- The formation of UBC and NO from coal was successfully predicted.
- Suppression of NO formation under a low-SR condition was found using the model.
- The heterogeneous combustion reaction rate was calculated considering the RPM.

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ABSTRACT

Coal in pulverized form has been utilized to generate heat for boiler operation, most of which is used to run power generation plants. Owing to the issues of the pollutant gas production within the pulverized-coal-fired boiler, the CO, NO, and unburned carbon (UBC) concentrations need to be reduced despite the formation of SO₂, which is also a potential pollutant. In order to study the pollutant generation mechanism of pulverized coal and predict its contents, the drop-tube furnace (DTF) experiment has been established and used extensively by many researchers worldwide. The DTF experiment itself, including the sample preparation processes, takes a long time to be performed. Therefore, in the present study, DTF modeling using one-dimensional numerical simulation is established for the rapid, good-accuracy prediction of the output gas and UBC concentrations. The DTF model is successfully established and found to provide results with trends similar to those of experimental results. Coal with high reaction rates is observed to have higher NO emissions than that with low reaction rates; this is attributed to a higher peak temperature in the combustion cloud around the coal particles, which leads to thermal NO formation. Suppression in the NO formation rate is observed in low-stoichiometric-ratio combustion, even under high-temperature conditions. The existence of a high CO gas concentration would assist in suppressing the NO formation during the combustion of coal char particles.

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1. Introduction

Coal in pulverized form has been utilized to generate heat for boiler operations, most of which is used to run power generation plants. The grinding of coal into pulverized form requires a long time and large amounts of energy and money. However, this system increases the space efficiency of an entrained-type power

generation plant in comparison to that of other types of power generation plant, such as fixed-bed or fluidized-bed plants, with an equivalent power generation output [1]. Therefore, entrained-type pulverized-coal-fired boilers are widely used worldwide. Pulverized coal particles ground using a pulverizer have a broad size distribution, which corresponds to an 80% mass fraction of well-pulverized coal particles with sizes smaller than 200 mesh [1,2]. The small size of the coal particles implies an increased surface area, which naturally promotes the combustion process [3–5]. Although the particle size of the coal is reduced, much unburned carbon (UBC) remains within the fly and bottom ashes after

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combustion occurs. Large amounts of UBC reduce the boiler total efficiency, which can create significant losses in economic value. In addition, the remaining UBC within the ash increases the difficulty of the ash disposal process. The UBC mass fraction within the fly and bottom ashes is considered good when under 5%. A UBC content of <5% means that the ash is acceptable for disposal, and it also indicates that the heat value from the coal was adequately utilized. The UBC mass fraction in the ash of six power plant units in Korea from different regions, namely S, Y, H, D, T, and B, is uniformly under 8% on average each year from 2008 until 2013 (see Fig. 1a). However, if the data are observed thoroughly, in many cases UBC generation is high (see Fig. 1b). Therefore, a study on UBC reduction mechanisms should be conducted to avoid large amounts of UBC contents within the ashes.

Generally, power plants in Korea use the 6080 cal/g coal calorific value as the standard for pulverized-coal-fired boilers. The coals that satisfy this heating value are usually bituminous-class coal. Bituminous coal has a higher price per energy unit than the other lower-rank coals such as sub-bituminous or lignite. Therefore, for economic reasons, sub-bituminous coal is also co-fired in order to economize the power generation costs. Low-rank coals generally have different characteristics than bituminous coals; they have higher moisture and volatile matter and lower fixed carbon and ash contents. The combustion characteristics are usually better than those of bituminous coal because of the high porosity developed in the coal after the devolatilization process. Some problems of low-rank coal utilization include the combustion being finished faster than that of the designed coal and the ashes' high alkaline metal contents, which lower the ash fusion temperature, which in turn leads to slagging in the burner and fouling in the heat exchanger.

In the pulverized-coal-fired boiler, coal particles are injected into the combustion zone of the reactor; in this case, a drop-tube furnace (DTF) was utilized to simulate the real situation in the boiler. The injected pulverized coal is blown by a pneumatic system for the carrier gas flows. The coal particles then receive heat from the wall of the preheated combustion zone. Once the coal particles are hot enough to be ignited, they combust inside the combustion zone. With the aim of understanding the mechanism of gas production accompanying the combustion of the coal particles, as well as determining the mass fraction of UBC, the DTF experiment has

been established and used extensively by many researchers worldwide [6–12]. This experiment represents the actual conditions inside the combustion zone with a lower mass flow rate and temperatures of up to 1600 °C. Moreover, the ambient gas composition can be controlled easily using mass flow controllers (MFCs).

The experiment itself, including the sample preparation processes, takes a long time to be performed. Furthermore, owing to the unstable coal feeding rate, each experimental condition needs to be repeated up to three times in order to obtain accurate average values for the UBC, NO, and CO concentrations. The experiment must be performed repeatedly in order to obtain the full map of the emitted combustion gases and generated UBC. Therefore, in the present study, DTF modeling using a one-dimensional numerical simulation was established for the rapid, good-accuracy prediction of the output gas and UBC concentrations. In addition to the DTF experiment, thermogravimetric analysis (TGA) was performed to obtain the input parameters for the simulation: the char combustion kinetics and the random pore model (RPM) parameter. These experimental methods and the RPM are well established and used extensively by researchers [13–16], though in some temperature ranges, the data of some coals do not fit well to the model.

2. Experiments

2.1. DTF

The experimental equipment comprised an alumina tube, a heater, a pneumatic-vibration (PV) coal feeder, some MFCs, a vacuum pump, a gas analyzer, a sample probe, and water jackets placed in the upper and lower parts. The schematic of the equipment is shown in Fig. 2. The MFCs were used to control the flows of nitrogen and oxygen gases in order to create an atmosphere inside the combustion zone similar to that inside the combustion zone in a real-scale boiler. The exhaust gases were then measured in the lower part by using the gas analyzer.

In order to observe the combustion characteristics of the coal in greater detail, only a single stage (one reaction zone) was used, even though the experimental apparatus was capable of supporting a double-stage combustion experiment. The experimental conditions were set to have stoichiometric ratios (SRs) of 0.8, 1.0, and 1.2. The SR value of 1.0 indicates that combustion occurs at

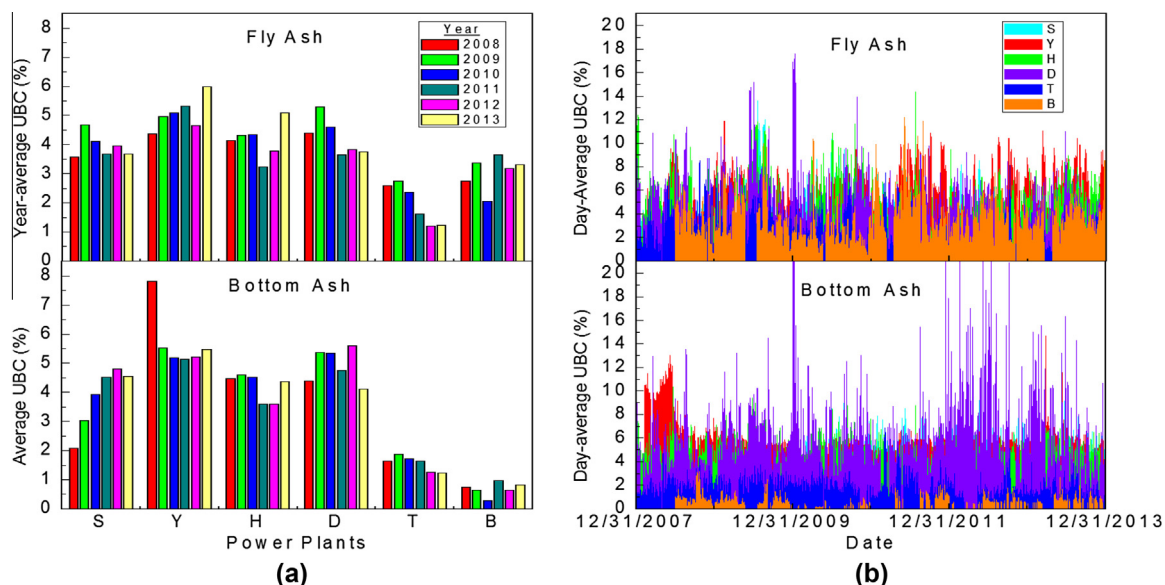


Fig. 1. (a) Average annual UBC contents in fly and bottom ash from six Korean power plants from 2008 to 2013 and (b) daily UBC contents in fly and bottom ash from these Korean power plants between 2008 and 2013.

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